Chapter 9

Concrete Mix Design

CONCRETE MIX DESIGN

1. GENERAL

Mix design is a process that consists of two interrelated steps:

(1) Selection of the suitable ingredients (cement, aggregate, water and admixture) of concrete and

(2) Determination of their relative quantities to produce as economically as possible concrete of appropriate workability, strength and durability

Although many concrete properties are important, most design procedures are aimed at achieving a specified compressive strength at a given workability; it is assumed that if this is done, the other properties will also be satisfactory. An exception represent the resistance to freeze-thaw and other durability problems (for instance sulphate resistance), which require special attention in the mix design.

2. BASIC DESIGN CONSIDERATIONS

2.1 Costs

The cost of concreting is made up of material costs, plant and labour expenses. Except for some special concretes, the costs of labour and equipment are, however, to a large extent independent of the type and quality of concrete produced. It is therefore the material costs that are most important in determining the relative costs of different mix designs. Since cement is much more expensive than aggregate (see Table 1), it is clear that minimising the cement content is the most important single factor in reducing concrete costs (see also Figure 1).

Table 1: Prices of concrete constituents in Switzerland per ton (approx.)

Concrete constituent	Price (CHF)
OPC cement silo	~~110.--~~ 150
OPC cement bag	125.-- 180
Sand fraction 0/4 mm	20.20
Gravel fraction 4/8 mm	16.90
Gravel fraction 8/16 mm	12.--
Gravel fraction 16/32 mm	9.40

To economise on material costs, the proportioning should minimise the cement content without scarifying concrete quality. Since the quality depends primarily upon the w/c ratio, the water content should be reduced to lower the cement content. Some of the steps to minimise water and cement contents are to use:

- the stiffest practicable mixture
- the largest possible maximum size of aggregate
- the optimum ratio of fine and coarse aggregates

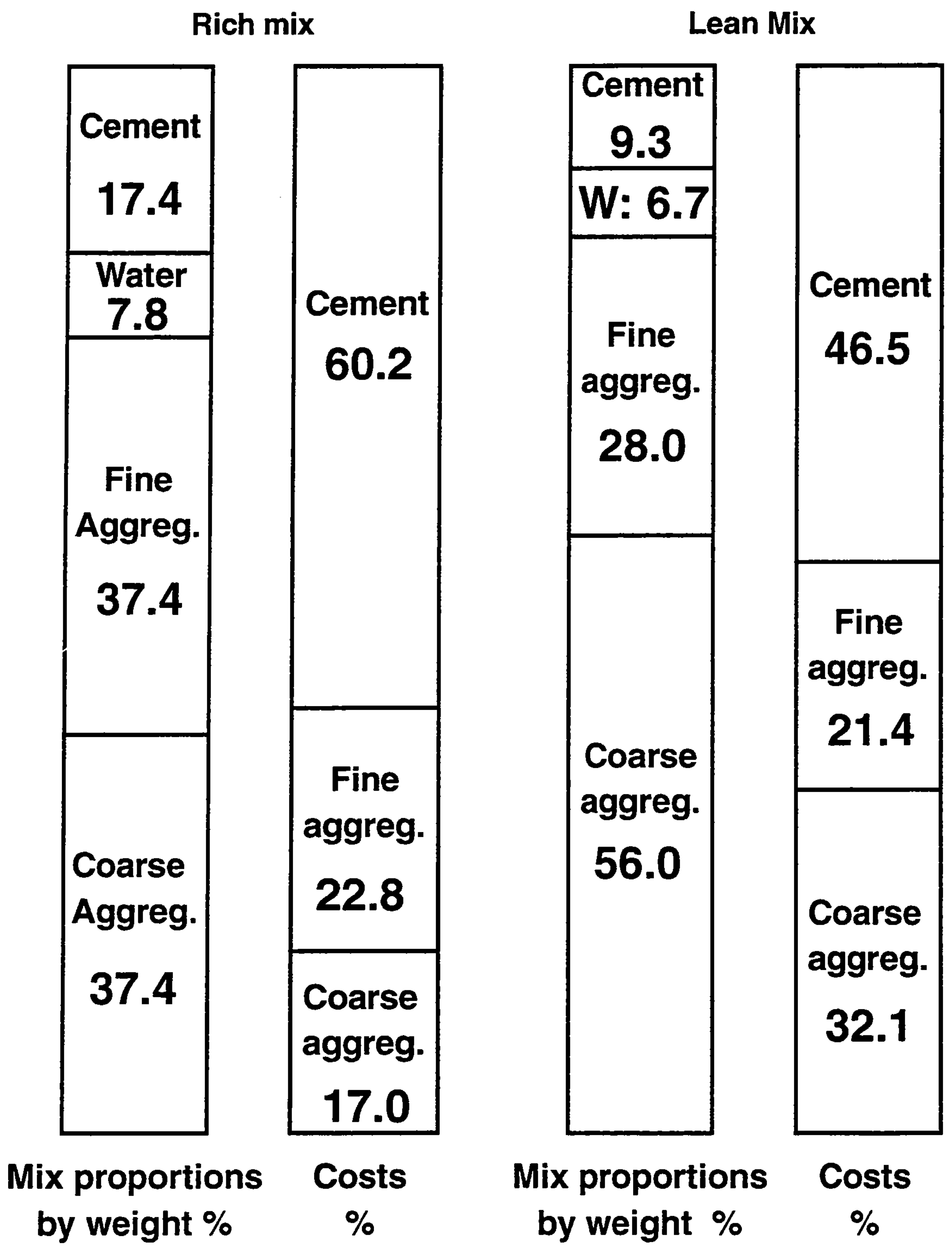
The cement reduction is, however, often restricted by specifications stating the minimum cement content (see Table 2).

Table 2: Minimum cement content in concrete for different national standards (kg/m³)

Type of concrete	Germany DIN 1045	Switzerland SIA 162	France* NF P-18-305	USA	England
Plain concrete	≥ 100	--	--	--	--
Reinforced/pre-stressed concrete	280 (OPC 25) 240 (OPC 35)	300	for class 250 and higher: $(250 + B)/D^{1/5}$	none	none

* B = compr. strength in bar; D = max. aggregate size

Figure 1: Costs of concrete: material costs



It should be noted here that in addition to cost, there are other benefits by using a low cement content; shrinkage will in general be reduced and there will be less heat of hydration. However, if the cement contents are too low, they will diminish the early strength and durability of concrete and will make uniformity of the concrete a more critical consideration.

Besides the cement reduction as such, there is also an interesting potential to reduce costs through the replacement of cement by mineral components (e.g. fly ash or ground blast furnace slag). Prerequisite is of course that mineral components of good quality are available at the concrete plant at convenient prices.

To determine the most economical mix proportions, the relative costs of fine and coarse aggregates should also be taken into consideration. Since admixtures to reduce the water requirement will increase material costs, it should be assessed in each case whether their use is justified by the savings in labour costs and cement cost eventually.

The economy of a particular mix design should also be related to the degree of quality control that can be expected on a job. At least on small jobs, it may be cheaper to overdesign the concrete than to provide extensive quality control that would be required with a more cost-efficient concrete.

2.2 Workability

Clearly, a properly designed mix must be capable of being placed and compacted properly with the equipment available. Finishability must be adequate, and segregation and bleeding should be minimised. As a general rule, the concrete should be supplied at the minimum workability that will permit adequate placement. The water requirement for workability depends mostly on the characteristics of the aggregate rather than of those of the cement. Where necessary, workability should be improved by increasing the mortar content rather than by simply adding more water or more fine material. Thus, co-operation between the mix designer and the contractor is essential to ensure a good concrete mix. In some cases, a less economical mix may be the best solution.

2.3 Strength and durability

In general, concrete specifications will require a minimum compressive strength. They may also impose limitations on the permissible w/c-ratios and minimum cement contents. It is important to ensure that these requirements are not mutually incompatible. It is not necessarily the 28 day strength that is most important; strength at other ages may control the design.

Specifications may also require that the concrete meet certain durability requirements, such as resistance to freezing and thawing, or chemical attack. These considerations may provide further limitations on the w/c-ratio or cement content and in addition may require the use of admixtures.

3. SPECIFICATIONS FOR CONCRETE MIXES

There are three systems that can be applied to specify structural concrete. These differ with respect to the basis of specification, responsibility for the mix design and the parameter by which the concrete is judged for compliance, as indicated in Table 3.

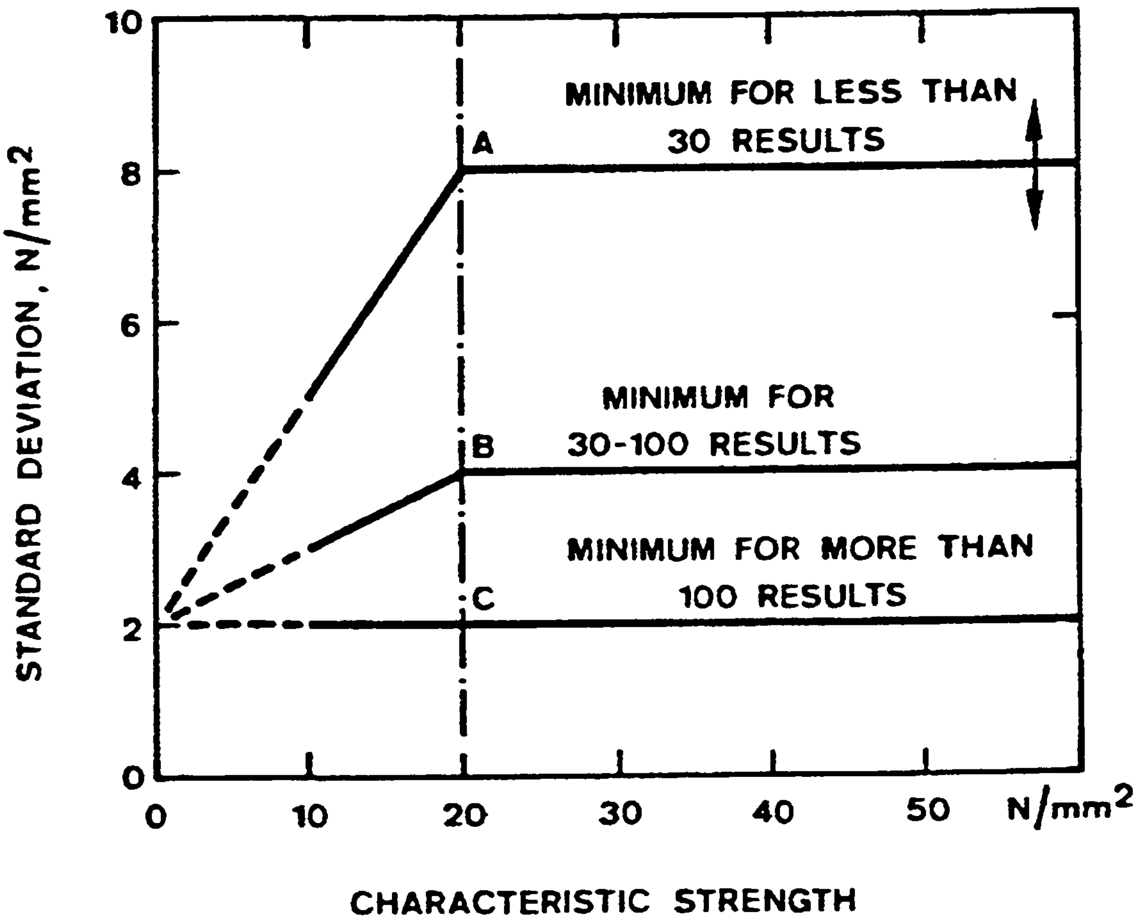
Table 3: Types of concrete mixes and their method of specification

	Type of mix	Designed mix	Codified mix	Prescribed mix
Design stage	Basis of specification	Strength	Mix Proportions	Mix Proportions
	Strength classes	all	≤ 25 N/mm^2	all
Production stage	Responsibility for mix design	Producer	National code or specification	Purchaser
	Permitted materials	Any materials complying with National Standards	Restricted range of materials complying with Nat. Standards	any
	Strength testing for information	Basis of mix	Not usually necessary	Desirable especially for higher strength classes
Compliance stage	Basic parameters of concrete for compliance testing	Strength	Mix proportions	Mix proportions

Designed mixes

The mix should be designed to have an adequate margin of strength between the specified characteristic strength or the designed mean strength based on the standard deviation obtained through experience. If there are no previous data, or if there are less than 30 results obtained under equal conditions (same plant, source of materials, and supervision), the proposed minimum value for standard deviation as per curve A (Figure 2) should be considered.

Figure 2: Proposed minimum values for the standard deviation



If there are between 30 and 100 results, the standard deviation should be the value obtained but not less than that given by curve B, i.e. for characteristic strength equal to or greater than 20 N/mm^2, the minimum standard deviation is 4 N/mm^2. For more than 100 results curve C gives the minimum standard deviation.

These values of standard deviation will be used for the calculation of characteristic strength.

Designed mixes are the most common types of mixes used in concrete practice.

Codified mixes

Codified mixes are recommended in National Standards or Codes and are based on the characteristics of the cement and aggregates available in each country. The adequacy of the structure is generally assured since the cement content will usually be greater than that of the corresponding designed mixes.

Codified mixes are restricted to the lower strength classes of concrete and may be made only with restricted types of materials. They are sometimes used as approximate guidelines for designed mixes.

Prescribed mixes

Prescribed mixes are applied when the purchaser wishes to specify the mix proportions to be used. There are a number of circumstances which call for such mixes; for example, if the purchaser knows that with local materials certain mix proportions will produce concrete of the required proportions, or if he requests the use of specific mixes because he wants a concrete with special characteristics (high or low density, etc.). Since the purchaser designs the mix, it is also his responsibility to ensure that the strength and other requirements for the safety of the construction are met.

4. PROCESS OF MIX DESIGN FOR NORMAL-WEIGHT CONCRETE

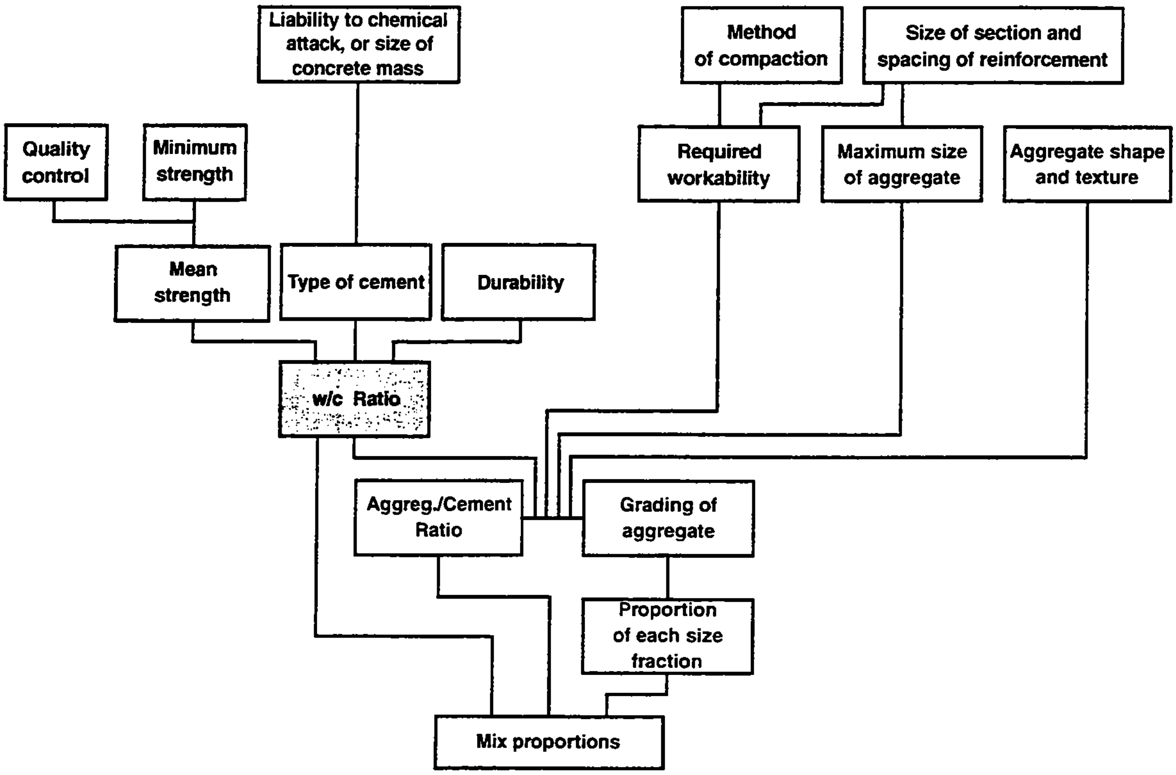
Before a concrete mix can be designed and proportioned, certain points of information should be known:

1) Size and shape of structural members
2) Spacing and diameter of reinforcement
3) Required strength
4) Exposure conditions (requirements for durability and chemical attack)
5) Placing and compaction methods
6) Basic material quality data on cement and aggregate

It is up to the design engineer and the architect to provide the information for points 1), 2) and 3). The information for points 5) and 6) can be obtained from the contractor firm and material supplier. As to point 4), the requirements for exposure conditions are normally specified in the standards.

The basic factors that have to be considered in determining the mix proportions are represented schematically in Figure 3.

Figure 3: Basic factors in the process of mix design



The American Concrete Institute ACI recommends a maximum permissible w/c ratio for different types of structures and degree of exposure. The European Norm EN 206 for concrete describes as well the maximum permissible w/c ratio, minimum cement content, the minimum air content and range of aggregate grading for the different exposure conditions.

It should be explained that a design in the strict sense of the word is not possible: many of the material properties and effects in the concreting process cannot be truly assessed quantitatively, so that we are really making no more than an intelligent guess at the optimum combinations of the ingredients on the basis of the relationships established empirically. Therefore, we not only have to calculate or estimate the proportions of the available materials, but must also make trial mixes. Properties of trial mixes are checked and adjustments in the proportioning are made until a fully satisfactory mix is attained.

Trial mixes are usually relatively small batches made with laboratory precision so that a certain security factor should be calculated when using laboratory results on large job-site batches.

The calculation of material quantities for mix design of ordinary normal-weight concrete is based on the absolute volume of the ingredients:

Volumes in 1m^3 compacted fresh concrete:

$$\frac{C}{\delta_c} + \frac{A}{\delta_A} + \frac{W}{\delta_w} + P = 1000\left[dm^3\right]$$

C = cement content in kg/m^3
A = aggregate content in kg/m^3
W = water content in kg/m^3
P = air pores;
in compacted non-air-entrained concrete: 10 ÷ 20 dm^3/m^3;
in air-entrained concrete: 30 ÷ 70 dm^3/m^3
δ_c = bulk density of cement kg/dm^3
δ_A = bulk density of aggregate kg/dm^3
δ_w = bulk density of water = 1.0 kg/dm^3

Guide values for the above bulk densities are given in Table 4

Table 4: Guide values for bulk densities δ in kg/dm^3

Cements		**Aggregates**	
Portland cement	3.05 - 3.15 kg/dm^3	Sand, gravel	2.6 - 2.65 kg/dm^3
Blast furnace slag cement	3.0 kg/dm^3	Limestone	2.7 kg/dm^3
Pozzolanic cement	2.9 kg/dm^3	Basalt	2.9 kg/dm^3
		Volcanic gravel + sand	2.1 - 2.4 kg/dm^3
		Lightweight aggregate for structural lightweight concrete	0.4 ÷ 1.9 kg/dm^3

There are various methods to calculate a concrete mix. The difference between those methods is not to be attributed to the basic factors but rather to the mode of calculation and adjustment applied. As example, three methods to calculate the mix design of normal weight concrete are compared in Table 5.

Here, only the general principle of the mix design procedure shall be briefly presented (see also example of mix design in the next chapter):

First of all, the maximum permissible w/c-ratio for the required concrete strength has to be fixed; this value can be taken from the relationship w/c-ratio - concrete strength in function of the strength class of the cement.

Then, the required water content w (mixing water plus surface humidity of aggregate) has to be defined. The water content w can be estimated based on the needed consistency and the aggregate grading and modulus respectively.

Table 5: Example of methods to calculate a concrete mix

	Country & Standard (Code)		
Step No.	**United States ACI**	**England Dep. of Environment**	**W. Germany DIN**
1.	workability = slump	mean strength (w/c-ratio)	cement quality
2.	max. size of aggregate	water content (workability)	consistency
3.	mixing water + (air content)	cement content	grading of aggregate
4.	w/c ratio	aggregate content	water content
5.	cement content	fine/coarse aggregate	concrete strength
6.	coarse aggregate content	trial mixes	w/c ratio
7.	fine aggregate content		cement content
8.	adjustment for aggregate moisture		weight of ingredients
9.	trial batch adjustments		trial mix
For details consult:	ACI 211.1-91, ACI Manual of Concrete Practice, American Concrete Institute, USA	A. Neville: Properties of concrete. Chapter 14. Mix Design., Longman, 1995	K. Walz: Herstellung von Beton nach DIN 1045. Beton-Verlag GmbH, Düsseldorf, 1971.

The necessary cement content c in the concrete mix can accordingly be calculated with the w/c-ratio and the water content w by means of the following formula:

$$c = w/(w/c)$$

Knowing the cement and water content, we can calculate the required amount of aggregate using the equation on the absolute volume of the ingredients (assumption on air pores p). Thus, the weight of oven dry aggregate A for 1 m^3 of concrete is:

$$A = \delta_A\,(1000 - c/\delta_c - w - p)$$

If humid aggregate is used, then the amount of surface humidity during concrete preparation has to be determined and to be included for the proportioning of the mixing water and the aggregate. The mixing water is calculated by subtracting the content on surface humidity from the water content w. For the proportioning of the aggregate, the amount A calculated according to the above equation has to be increased by the content of surface humidity.

If plasticising concrete admixtures (e.g. water reducers or air entrainer) are added to the concrete, the water content w for a given consistency is reduced. The fine air pores produced by the addition of air entrainer improve also indeed the workability, but they reduce at the same time the concrete strength; in case of air entrained concrete, the real water content has therefore to be adjusted for both the plasticising and strength reducing effect of the air entrainer.

5. EXAMPLE OF MIX DESIGN CALCULATION

For illustration, a mix design shall be calculated here with the aid of Table 6 and Figures 4 to 6 from DIN standard 1045.

In our example, the concrete requirements shall be as follows::

- consistency: compaction factor 1.20
- strength class: B 35
- exposure condition: interior of building (thus no further limitations on w/c-ratio and cement content)
- max aggregate size: 32 mm
- aggregate grading: between sieve curves A and B (see Figure 6)

The available concrete components are:

- cement class Z 35 (density 3.10 kg/dm^3)
- aggregates:

  sand 0/2 mm (density 2.52 kg/dm^3)
  natural aggregate 2/8 mm (density 2.62 kg/dm^3)
  natural aggregate 8/32 mm (density 2.72 kg/dm^3)

  with the following grading:

Passing sieves (%)	0.25mm	0.5 mm	1 mm	2 mm	4 mm	8 mm	16 mm	32 mm
sand	6	50	80	97	100	100	100	100
aggr. 2/8mm	3	8	10	10	55	95	100	100
aggr. 8/32 mm	2	2	3	3	4	6	50	100

The average compressive strength tested on three cubes in one trial batch for the concrete strength class B 35 should be at least 45 N/mm^2 (see Table 6). Accordingly, the water/cement-ratio can be estimated from Figure 4; it amounts to 0.47.

Aiming at a grading of the aggregate mixture between A and B sieve curves, the estimated amount of aggregate fractions is:

- sand: 25 vol.%
- 2/8 mm: 23 vol. %
- 8/32 mm: 52 vol. %

The resulting grading of the aggregate mixture is thus:

Passing sieves (%)	0.25 mm	0.5 mm	1 mm	2 mm	4 mm	8 mm	16 mm	32 mm
	3	15	24	28	39	49	74	100

With the corresponding grading modulus 4.68 and the concrete compacting factor of 1.20, the water content w estimated from Figure 5 is 153 kg/m^3.

The calculated cement content c is therefore:

$153 : 0.47 = 325$ kg/m^3 of concrete

The volume proportion of the oven dry aggregate mixture in 1 m^3 of concrete can then be calculated by means of the absolute volume of the ingredients (assuming an air content P of 15 dm^3):

$$A = 1000 - (c/3.10 - w - P) = 1000 - (325/3.10 - 153 - 15) = 727 \text{ dm}^3$$

consisting of:

727 x 0.25 x 2.62 = 476 kg of sand
727 x 0.23 x 2.62 = 438 kg of fraction 2/8 mm
727 x 0.52 x 2.72 = 1028 kg of fraction 8/32 mm

That means 1942 kg of aggregate mix in 1 m^3 of concrete.

The mix design is thus:

aggregate	1942 kg/m^3
cement	325 kg/m^3
water	153 kg/m^3

resulting in 2420 kg/m^3 of fresh compacted concrete.

Table 6: Requirements for concrete in preliminary test

Group of concrete	Strength class	Required compr. strength (N/mm^2)[1), 2)]	Required consistency values[2)]
B I	B 5 B 10 B 15 B 25	≥ 11 ≥ 20 ≥ 25 ≥ 35	K 1: v = 1.30...1.26 K 2: v = 1.15...1.11 a = 39...40 cm K3: v = 1.06...1.04 a = 48...50 cm
B II	B 35 B 45 B 55	40 + m[3)] 50 + m[3)] 60 + m[3)]	according to requirements of the site, incl. margin

1) average compressive strength of three cubes of one batch
2) site-mixed and ready-mixed concrete, not for concrete in concrete works
3) choose margin m according to experience, otherwise m ≥ 5 MPa are to be used

Figure 4: Relationship strength versus w/c ratio

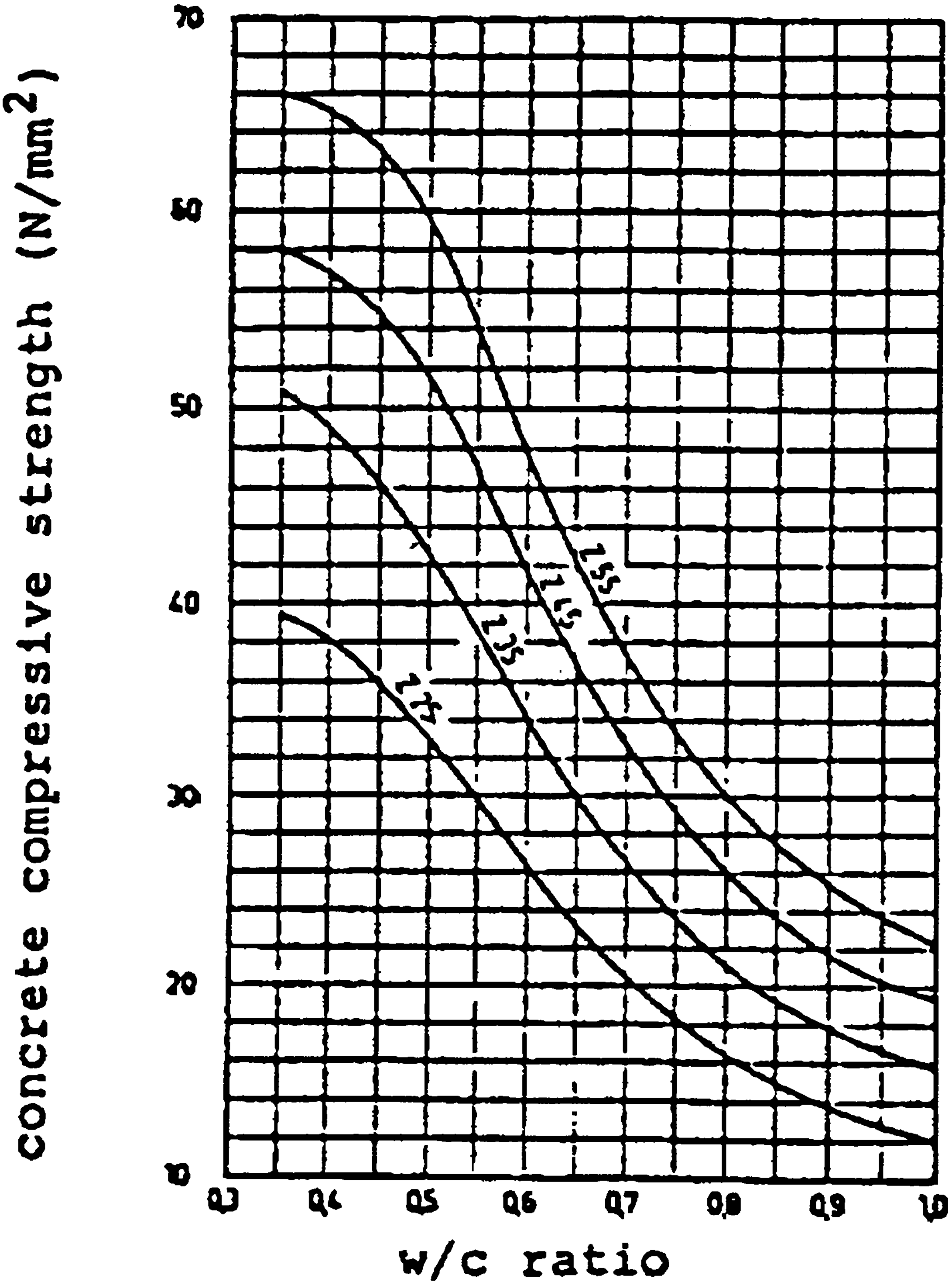
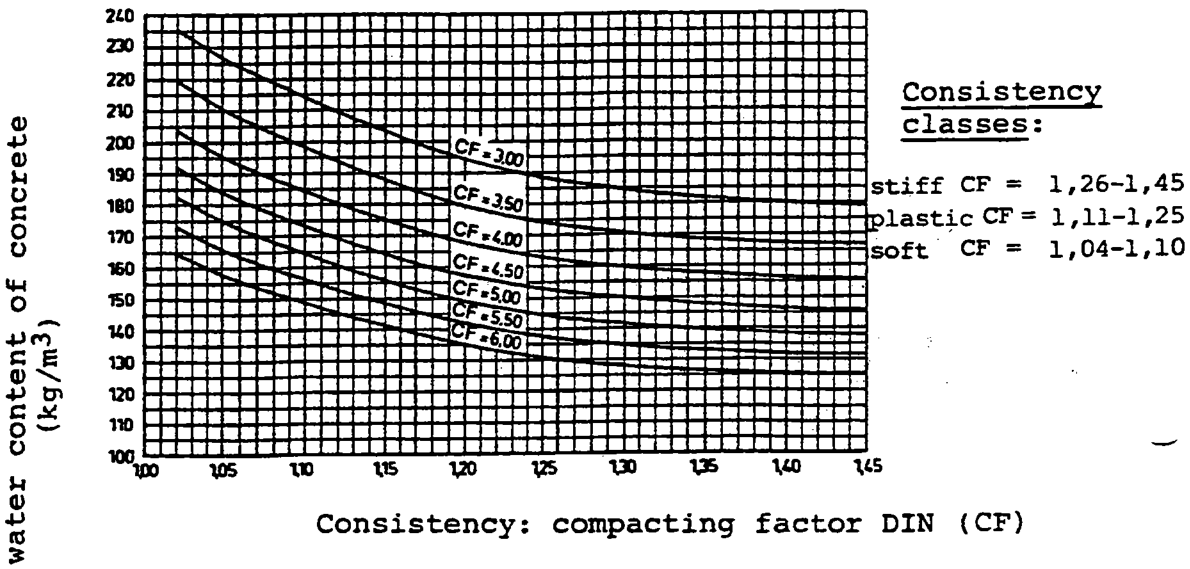


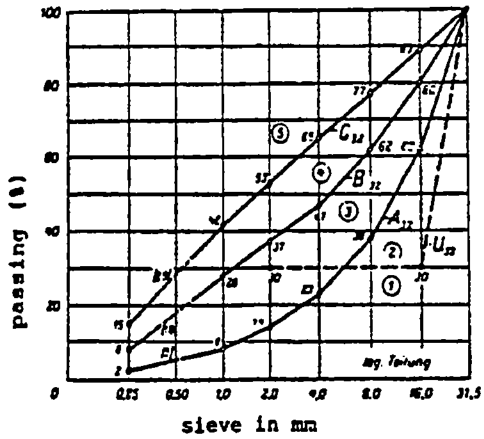
Figure 5: Relationship between consistency, grading modulus and water content of concrete

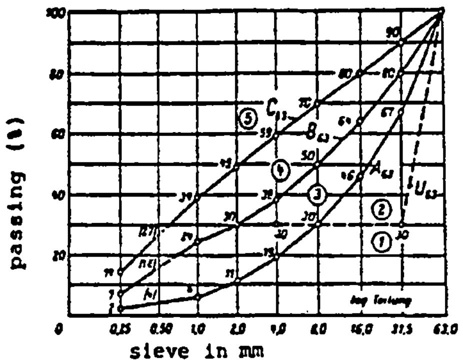


Correction of water content:

- by using crushed aggregate + 5 ÷ 10%
- by using plasticisers - 5%
- by using air-entraining agents - 1% per 1% of air content

Figure 6: Standard grading curves





Classification of grading:

1 unfavourable
2 gap-graded mixes
3 favourable
4 serviceable
5 unfavourable

6. CONCLUDING REMARKS

There are several well established methods to calculate concrete mixes. Given the variability of the properties of ingredients and the difficulty in describing them, the results of these calculations are, however, really only guesses. On the other hand, such methods are concerned basically with the technical aspects of mix design without proper consideration of the economical side of the problem.

The establishment of a proper concrete mix design will always involve the preparation and testing of trial mixes and consecutive adjustments. The experience and knowledge on the influence of the various factors upon the properties of concrete can of course help to improve the first guess and limit the number of trial mixes to be tested.

To facilitate the selection of the optimum concrete mix design (also from the economic point of view), more and more computer based tools are used nowadays in practice. Such tools do not replace experience, but allow to explore more quickly the different alternatives and to arrive faster at the optimum solution.

7. LITERATURE

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